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The purpose of this work was to develop a stronger theoretical foundation for the Juan-Pappas eigensystem realization algorithm. This technique is a widely used method from impulse response data. Details and references are included in the report.

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State Space Identification and Active Structural Control for the ACTEX Flight Experiment

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1 Introduction

This ASSERT F49620-94-1-0409 grant is linked with the parent grant F49620-95-1-0019 entitled Robust, Nonlinear Feedback Control. Funding under this grant was used to support one graduate student, namely, Mr. James Akers. Mr. Akers was awarded the PhD degree in June 1997.

A description of the theoretical and experimental research conducted by Mr. Akers under the direction of the Principal Investigator is given in Sections 2 & 3. Concluding remarks is given in Section 4. Relevant publications are listed in the References.

The research described in this report was carried out in anticipation of the ACTEX Flight Experiment. Preliminary data from ACTEX is being evaluated by program personnel [15].

Mr. Akers' progress under this grant was excellent. He has been involved in both theoretical and experimental activities and his research is expected to have a significant impact on control applications.

2 Theoretical Research

Our initial goal under this project was to develop a stronger theoretical foundation for the Juang-Pappas eigensystem realization algorithm (ERA) [13] [14, pp. 133-137]. This technique is a widely used method for constructing structural models from impulse response data. In practice such data is obtained by computing the inverse Fourier transform of the frequency response function. The impulse response data provides a Markov block Hankel matrix whose singular value decomposition is used to construct the structural model. This method operates in a batch mode where accumulated data is processed off-line to create the structural model.

In [2] we analyzed the stability of reduced-order models obtained from the ERA algorithm combined with modal truncation as determined by the singular value decomposition of the Markov block Hankel matrix. This analysis involved error bounds associated with model truncation based upon finite-interval Gramians. Sufficient conditions for asymptotic stability of the reduced-order model along with error bounds in the presence of measurement noise were given.

Next we developed the *recursive ARMARKOV/Toeplitz identification algorithm* [1, 5, 6, 7] for recursive on-line identification based upon the approach of [11] and partially developed in [10, 12]. This algorithm provides the first-stage in a two-stage identification algorithm, where ERA is used as the second-stage to construct minimal realizations from the estimated

Markov parameters.

ARMARKOV models relate the current output of a system to past outputs as well as current and past inputs. ARMARKOV models have the same form as ARMA models, but explicitly involve Markov parameters. Appropriate stacking of these ARMARKOV models yields a block-Toeplitz weight matrix which maps a vector of past outputs and inputs to a vector of the current and past outputs. A recursive update law for the estimated weight matrix is constructed based upon a constrained gradient. This constrained gradient preserves the block-zero structure of the weight matrix and, in the presence of a persistent input sequence, guarantees that the estimated weight matrix converges to the actual weight matrix. Estimates of the Markov parameters can be directly extracted from the converged weight matrix for use in ERA.

The principal mathematical contribution of this work is a rigorous proof of the convergence of the recursive ARMARKOV/Toeplitz identification algorithm in the presence of a persistent input sequence [1, 5, 6, 7]. The input sequence, which need not be white noise, can be tested a posteriori to determine if it satisfies the persistency conditions. In practice the persistency conditions are satisfied by a broad class of input sequences.

Mr. Akers also developed alternative recursive and batch techniques based upon ARMARKOV models. The alternative recursive technique incorporates an ARMARKOV model in a Toeplitz structure utilizing a quasi-Newton update direction to estimate the Markov parameters [9]. The alternative batch technique generalizes ARMA least-squares to incorporate an ARMARKOV model [8].

By combining the recursive ARMARKOV/Toeplitz identification algorithms with ERA we have demonstrated a highly automated on-line identification technique that can readily be implemented in practical application. This approach provides the means for continually updating the structural model for modal refinement and damage detection. Similarly, by combining the least-squares ARMARKOV identification algorithm with ERA we have constructed a highly automated off-line identification technique.

3 Experimental Research

To illustrate the method Mr. Akers developed an experimental testbed involving an acoustic duct with multiple speakers and microphones. The acoustic duct provides a challenging testbed due to $0.5\% - 2\%$ modal damping and high modal densities. These characteristics are shared by large flexible space structures and are difficult to handle by many identification techniques. In preliminary research this setup was used to validate techniques for modal identification as the basis for feedback control [3, 4].

The acoustic duct is constructed from a 39 inch long 4 inch diameter PVC pipe with open-closed boundary conditions. The output from the performance and measurement microphones was passed through a four pole analog Butterworth low pass filter with a cutoff frequency of 1250 Hz. The disturbance and control speaker inputs and the performance and

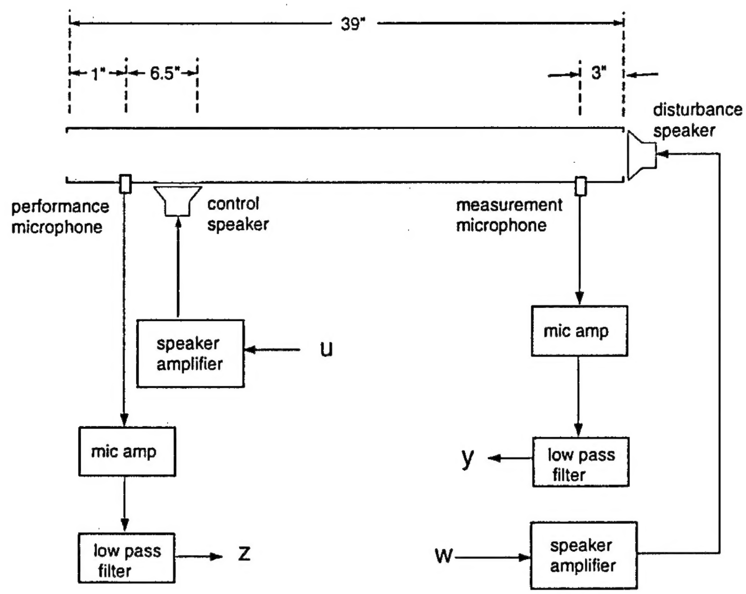

Figure 1: Experimental set up of acoustic duct.

measurement microphone outputs were recorded at a sampling frequency of 5120 Hz with a time-record length of 4096 data points spanning 0.8 seconds. The inputs $u(k)$ and $w(k)$ were chosen to be white noise. The experimentally measured frequency response was obtained using a spectrum analyzer with the frequency range chosen to be 0 - 2000 Hz with 1601 spectral lines of resolution. A schematic of the experimental set up of the acoustic duct is shown in Figure 1. The recursive ARMARKOV/Toeplitz/ERA identification algorithm [1, 5, 6, 7] produced a 44th-order realization of the dynamics from the disturbance speaker to the performance microphone. The frequency response of the 44th-order realization and the measured frequency response is shown in Figure 2.

Alternatively, the batch least-squares ARMARKOV/ERA identification algorithm [8] was also used with the same time record and produced a 46th-order realization of the dynamics from the disturbance speaker to the performance microphone. The frequency response of the 46th-order realization and the measured frequency response is shown in Figure 3.

4 Concluding Remarks

Under this ASSERT grant both recursive on-line and batch off-line time-domain identification techniques have been developed that can handle lightly damped and high order

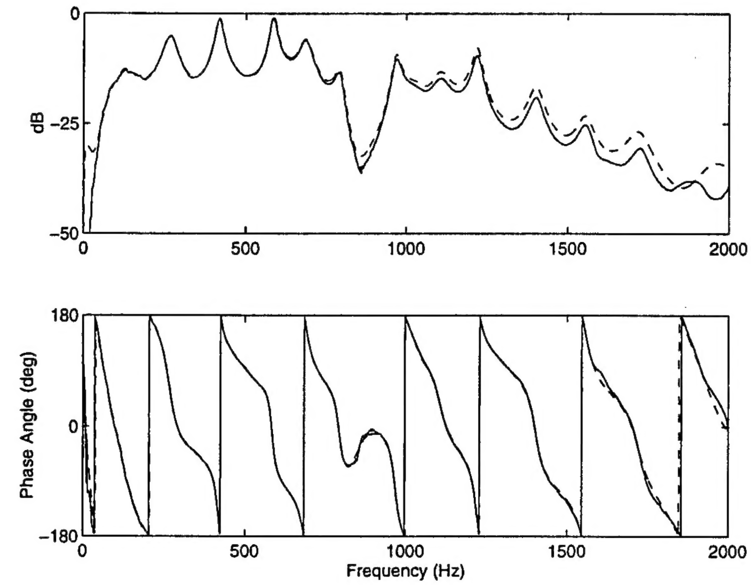

Figure 2: Recursive ARMARKOV/Toeplitz/ERA identification algorithm of the acoustic duct, frequency response of the 44th-order identified state space realization (dashed line) and experimentally measured frequency response (solid line).

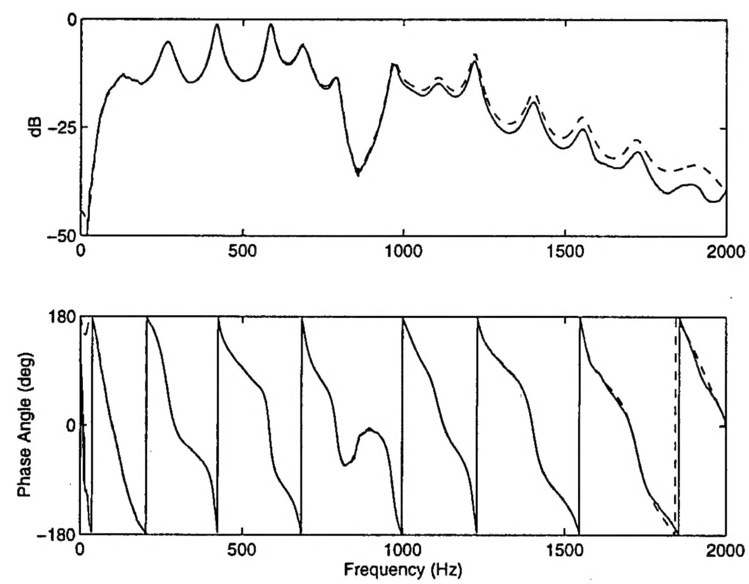

Figure 3: Least-squares ARMARKOV/ERA identification algorithm of the acoustic duct, frequency response of the 46th-order identified state space realization (dashed line) and experimentally measured frequency response (solid line).

systems. These algorithms directly identify the Markov parameters from the time-domain data which are then used in ERA to obtain state space realizations. These algorithms are conceptually straightforward and easy to implement. Numerical simulation and experimental results have shown the algorithms to be robust to measurement noise and model order underestimation.

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